Defense Technical Information Center
Compilation Part Notice

ADP014117

TITLE: High Frequency Acoustic Suppression - Experimental & Computational Overview

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Aging Mechanisms and Control. Symposium Part A - Developments in Computational Aero- and Hydro-Acoustics. Symposium Part B - Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs [Les mecanismes vieillissants et le controle] [Symposium Partie A - Developpements dans le domaine de l'aeroacoustique et I'hydroacoustique numeriques] [Symposium Partie B ...

To order the complete compilation report, use: ADA415749

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP014092 thru ADP014141

High Frequency Acoustic Suppression – Experimental & Computational Overview

Michael J. Stanek
Air Force Research Laboratory
AFRL/VAAI Bldg 45
2130 8th Street, Suite 1
Wright-Patterson AFB, OH 45433-7541, USA
Michael.Stanek@wpafb.af.mil

John A. Ross and Ian Wrisdale
Defence Evaluation and Research Agency
Bedford, MK41 6AE
United Kingdom
Jaross@dera.gov.uk

I. Abstract

The recent history of the relatively new field of high frequency acoustic suppression is outlined. Key experiments, actuator developments, and obvious applications are described. Differences between low frequency forcing and high frequency forcing are outlined, and definitions for the two regimes are offered. Preliminary first steps toward numerical simulation of the high frequency acoustic suppression are critiqued and compared to existing experimental evidence. Future research directions are briefly described.

II. Introduction

In fighter / bomber weapons bays, experience has shown that an open cavity at moderately high speeds can have a profound effect on internally carried weapons; their suspension equipment, separation characteristics, and the structural loads on the parent aircraft. Acoustic resonance causes high amplitude fluctuating acoustic loads in and near the bay, high enough to very quickly fatigue metal parts, and to damage sensitive electronics on "smart" weapons.

Vertical Take Off & Landing (VTOL), or Short Take Off, Vertical Landing (STOVL) systems (such as Harrier, or the new Marine variant Joint Strike Fighter (JSF)) suffer from a very similar sort of resonant acoustic situation as the weapons bay. Acoustic levels due to jet exhaust impingement resonance in the region between the ground plane and underside of the aircraft (during vertical takeoff or landing) are also (as in the weapons bay) potentially large enough to cause structural damage. For most of the discussions in this paper we will focus on the high–speed cavity resonance problem, because this serves well as a canonical resonance problem; and because the bulk of the exploration into high frequency acoustic suppression has been in this application.

Active flow control has been touted as a means to efficient suppression of resonant acoustic behavior in these various aerospace systems. Interest in active control methods centers around the promise of adjustable, optimal suppression for changing flight conditions. Acoustic suppression utilizing active flow control is traditionally achieved by seeding the unstable free shear layer traversing the cavity (weapons bay) with small amplitude disturbances (vortical, acoustic or otherwise). These "planted" disturbances grow and in successful cases, compete with and overwhelm the more dangerous naturally occurring disturbances (the ones which lead to acoustic resonance).

Most documented attempts in the literature to apply active flow control to high speed cavities have focussed on perturbing the shear layer traversing the bay at frequencies near the dominant Rossiter modes. We will refer to that type of forcing as "low frequency" forcing. We will offer a more formal definition of both low frequency and high frequency later in the discussion. These "low frequency" (LF) active flow control attempts have met with some moderate success, but in most cases there are still significant, energetic tones remaining in the acoustic spectra (after active suppression) which could be further reduced. References 1 through 7 display representative examples of this type of LF active cavity flow control. Overall suppression (reduction of the peak sound pressure level (SPL) across all frequencies) using these low frequency techniques are typically on the order of 5 to 10 dB reduction.

Paper presented at the RTO AVT Symposium on "Ageing Mechanisms and Control: Part A – Developments in Computational Aero- and Hydro-Acoustics", held in Manchester, UK, 8-11 October 2001, and published in RTO-MP-079(I).

One must keep in mind that this is the same level of performance that might be expected from no-moving-parts, zero complexity, passive leading edge spoilers (which these new active flow control techniques are in competition with) found on today's strike aircraft with weapons bays. All of this changed in 1997, when the first attempt was made to explore active flow control in cavities at frequencies orders of magnitude higher than the dominant Rossiter modes.

III. Groundbreaking Early Work

For the purposes of this discussion, we will define ACTIVE suppression as any technique which attempts to control the cavity shear layer by inputting a time-dependent disturbance of KNOWN frequency. The first tangible example of an active suppression technique capable of **simultaneously** suppressing multiple acoustic modes (not due to excessive leading edge mass injection) was published by McGrath and Shaw in 1997 [Ref. 2]. Figure 1 from Ref. 2 shows an acoustic spectra from a Mach .6 cavity case with no suppression invoked. Figure 2 shows the same case with one type of high frequency suppression device in use (a rod in crossflow). The technique yielded dramatic results, suppressing all tones simultaneously, and giving a tone reduction across all frequencies of over 30 dB! The same cavity was tested at Mach .8, and the results were very good, if not quite as dramatic. There was no hint or suggestion in this early work that there was any fundamental difference between low frequency and high frequency flow control. Unfortunately, research resources were shifted into so-called "low frequency" suppression techniques when McGrath and Shaw found that their particular rod in crossflow device failed to produce suppression of any significance above Mach 1. See experimental data marked "Shaw 94" and "Shaw 95" in Figures 3 and 4 (Ref. 8).

Meanwhile, in non-cavity related high frequency work, Wiltse and Glezer [Ref. 9] were focussed on attempting to show that very small scales within a shear layer could be directly excited, instead of relying on the so-called "energy cascade" to move excitation energy from "large scale / low frequency " forcing to the small scales. They cited the work of Yeung et. al. [Ref. 10] as a source of insight in this respect. Wiltse and Glezer perturbed a small-scale rectangular subsonic jet shear layer with an aluminum wedge excited by a piezoceramic material, shown in Figure 5. Figure 6 shows a velocity spectra taken from that experiment. Two observations of note in that experiment were the fact that forcing at very high frequency affected ALL frequencies within the spectra, and the fact that below a certain transition frequency, energy was being taken OUT of the low frequency portion of the spectra due to this high frequency forcing (See Figure 6).

Cain [Ref. 12] describes the results of the Wiltse and Glezer's experiment as "startling", because they convincingly demonstrated a flow control concept which was completely foreign to the established fluid dynamics technical community. The status quo opinion of how free shear flows CAN be controlled was until now represented by the 1984 review article of Ho and Huerre [Ref 13]. Ho and Huerre [Ref. 13] characterizes the perspectives of the 1070's and 1980's, demonstrating the link between large-scale structures and linear stability theory [Ref 12]. In essence, the Wiltse and Glezer experiment was "startling" because it seemed to violate the time-honored principles established by the Ho and Huerre review.

In 1997, Alan Cain [Ref. 14] first proposed the notion that very high frequency active forcing (within several orders of magnitude of the so-called Kolmogorov frequency) of the shear layer spanning the weapons bay could be very effective at suppressing resonant cavity tones, citing the earlier work of Wiltse and Glezer [Ref. 9] in free shear layers. Cain suggested that the likely cause of the suppression in the earlier McGrath and Shaw [Ref. 2] rod-in-crossflow experiments was the same high frequency mechanism studied in detail and described by Wiltse and Glezer.

Based upon Alan Cain's recommendation, and under sponsorship from Air Force Research Laboratory (AFRL), Boeing took steps toward applying HF forcing to the high-speed cavity problem. The first step was to use the same actuator as in the Wiltse & Glezer experiment (Figure 5) and to modify the original free-jet experiment by creating resonance (i.e. to "simulate" a cavity flow). This was accomplished by inserting a scattering "wedge" downstream of the jet exit in order to set up edge tones [Ref. 15].

Figure 7 shows two views of the Boeing rectangular nozzle, with the wedge actuators mounted to supply forcing near the nozzle lip. Figure 8 shows schlieren images of the experiment from the side, with the nozzle exit and scattering wedge visible. This figure also shows the tip of the wedge actuator just touching the edge of the jet shear layer. The left inset figure shows jet flow without excitation- the right inset shows it with excitation. Figure 9 shows the clearly evident edgetones in the unsuppressed spectra, and the resulting suppression with HF excitation. The forcing frequency (near 5 khz) is clearly visible in the spectra. Even though the forcing in this experiment is not at a very "high" frequency, relative to the naturally occurring edge tones, the results were encouraging. They at least showed the prospect for simultaneously reducing all the resonant tones by forcing at a single high frequency. Boeing also demonstrated in this experiment that forcing at a high relative frequency affected ALL frequencies below it (the same result which Wiltse and Glezer [Ref 9] showed for a non-resonant free shear flow several years earlier – see Figure 6).

The decision was made, based upon these encouraging results, to take several so-called high frequency devices into a $1/10^{th}$ scale cavity facility at DERA in Bedford, under a joint U.S. / U.K. cavity flow control testing program.

IV. 1st Supersonic High Frequency Acoustic Suppression

Stanek et. al. [Ref. 11] were the first to present a comprehensive evaluation of several high frequency devices, demonstrating the thesis of Cain, i.e. that the mechanism described in Wiltse and Glezer [Ref. 9] could indeed be used as a very effective cavity

acoustic suppression technique. This was accomplished by testing several "high frequency" devices, and then examining their performance for hints of behavior similar to that seen in Wiltse and Glezer's experiment. In Ref. 11, Stanek et. al. argued that high frequency acoustic suppression is based upon a fundamentally different physical mechanism than low frequency acoustic suppression, and that it is this physically based difference that allows for radically higher rates of acoustic suppression.

Ref. 11 is perhaps most important, because it presented the first example of successful use of HF acoustic suppression at realistic SUPERSONIC conditions. The primary driver for research into active flow control techniques in weapons bays is the inability of passive leading edge spoilers to provide reliable acoustic suppression above Mach 1. Ref 11 was significant, because it provided practical impetus for a host of new experimental and computational work, aimed at understanding the high frequency forcing effect in shear layers. Figures 3 and 4 [Ref. 8] show the superior supersonic performance of the "rod" devices described in Ref 11 (rod in crossflow, labeled "DERA 99") relative to other historical rod-in-crossflow data.

Reference 11 describes the four devices designed to generate high frequency pulses (relative to the dominant Rossiter cavity modes) which were tested at various Mach numbers in a 1/10th scale DERA cavity model. Effective HF devices consistently outperformed a typical "effective" LF device (spoiler), usually producing suppression on the order of 10 to 15 dB in excess of their traditional non-HF counterpart.

Effective HF devices all produced similar effects on the Rossiter tones (**simultaneous** reduction) and produced profound changes to broadband levels and slopes consistent with the early benchmark HF free shear layer experiments of Wiltse and Glezer [Ref. 9].

The high frequency devices tested in the DERA cavity model were; a powered resonance tube, an unpowered resonance tube, a piezoceramic-driven vibrating wedge, and a rod in cross-flow. We will start by showing the cast of devices, and follow this with some representative results from the best performing devices, the powered resonance tube, and the rod in cross-flow.

Figure 5 shows a close-up of the by now familiar piezo-ceramic driven wedge actuator (used in the original Wiltse and Glezer [Ref. 9] experiment) – this was the first of the four devices. Figure 10 shows a view of the second device tested, a rod-in-cross-flow, as it appeared installed in the DERA 1/10th scale cavity model. Figure 11 shows a schematic of the third device, a powered version of a resonance tube. Figure 12 shows a bank of powered resonance tubes as they were installed in the DERA cavity model. A fourth device, a passive resonance tube concept (not shown) was also included in the DERA / AFRL test matrix. Interested readers are referred to Refs. 16-18 for descriptions of the resonance tube concept, and are referred to Ref. 15 for a detailed description of the development of the resonance tube "packages" used in the DERA/ AFRL experiments.

The highest suppression levels in these tests were delivered by the powered resonance tube device. It delivered suppression across all frequencies of roughly 26 dB at Mach .85, and about 29 dB at Mach 1.19. See Figures 13 and 14 (curves labeled ".411 lbm/sec").

The performance of the rod-in-crossflow was also very impressive. It produced suppression across all frequencies of roughly 14 dB at Mach .85, and roughly 21 dB at Mach 1.19. See Figures 13 and 14 (curves labeled "rod in xflow").

The unpowered resonance tube and powered piezo-wedge proved to be essentially ineffective for acoustic suppression in these particular tests.

Interested readers are referred to Refs. 11 and 19 for details concerning the DERA wind tunnel setup, the cavity model, data acquisition, or data reduction.

Having described highlights of the performance of these new high frequency devices, we will now examine the behavior of these devices more closely, and contrast their performance with more conventional types of flow control.

V. Useful Suppression Categories

For the purpose of contrasting the different physical mechanisms responsible for cavity acoustic suppression, we find it convenient to define three categories of suppression; low frequency, high frequency, and zero frequency. It is also convenient to define two different classes of flow control; active and passive.

We define ACTIVE flow control (or active acoustic suppression) as any technique which produces its manipulation of the flowfield mainly through the introduction of time-dependent perturbations of a <u>known frequency</u>. Conversely, we define PASSIVE flow control (or in this case passive acoustic suppression) as any technique which derives the majority of its effect by manipulating gross, time-averaged (i.e. steady) quantities, <u>without</u> purposely inputting a perturbation of known frequency (recognizing, of course, that every flow control technique produces some unsteadiness – i.e. all real flows present or display varying degrees of unsteadiness).

Steady leading edge blowing, leading edge spoilers, and cavity rear wall sloping, are all good examples of zero frequency suppression techniques. They appear to derive MOST of their effect by decreasing the impact of vortex impingement on the rear wall of the cavity (Spoilers also seem to derive some of their suppression behavior from shed vorticity, which shows up as a

redistribution of energy among modes, and a shift in mode frequency). Low and high frequency suppression will be defined in subsequent sections.

VI. Representative Low Frequency Suppression Results

Analysts interested in the stability of a particular fluid state usually develop stability "maps" which outline the range of frequencies (at a particular Reynolds number, and for a particular mode of instability) over which disturbances are amplified. Stability analysis also yields growth rates as a function of instability frequency. The frequency of maximal instability growth rate is frequently coined the most "dangerous" frequency. Low frequency (LF) shear layer excitation (and consequently low frequency acoustic suppression) methods work by exciting a shear layer in the frequency range of its most "dangerous" instability mode. This corresponds to the "classic" view of shear layer flow control described in Ho and Huerre [Ref. 13]. The Rossiter modes in the self-sustained cavity resonance problem fall in this range of most "dangerous" shear layer excitation frequencies.

The acoustic source for the cavity resonance problem (which "forces" the shear layer at the cavity front wall) is the impingement of coherent vortical structures on the cavity back wall. If you eliminate coherent vortical structures, you eliminate the source of the forcing, and the cavity resonance disappears. One of the problems with low frequency forcing of the cavity shear layer (for acoustic suppression) is that YOU ARE STILL FORCING IN THE RANGE OF MOST AMPLIFIED DISTURBANCES. You may reduce acoustic levels by making the production of coherent structures less efficient (by detuning the cavity), but YOUR forcing frequency is still being amplified, still generating large scale coherent structures, and STILL impinging on the back wall of the cavity (producing noise). The most effective flow control strategy in the cavity problem would be to ELIMINATE large coherent structures, not replace one noise producing set with another at a slightly different frequency. We will see in the low frequency acoustic suppression data to follow evidence of the growth of undesirable modes in LF forcing which lead to lower than optimal levels of acoustic suppression.

In coining the term "high frequency", we are begging the question "what constitutes low frequency?". We will attempt to answer that question by presenting representative examples of low frequency cavity suppression. We will begin with "zero mass addition" perturbation techniques. The common theme among these devices is that they typically are able to produce only small perturbations, are reasonably effective at low (less than .5) Mach numbers, and are shown to lose their effectiveness when applied to cavity flows at realistic Mach numbers (Mach .8 to Mach 1.5).

We will then proceed to examine LF devices capable of providing suppression in the "military" Mach range of interest (Mach .8 to 1.5). Since pulsed air is a popular form of suppression technique, we will begin by first describing the effect of steady (zero frequency) leading edge blowing. We will then look at the additional benefit derived from pulsing (in positive mass addition pulsed blowing).

VI.1 Cavity Acoustic Control Using Low Frequency, Zero Mass Addition Forcing

Figure 15 [Ref 20, Cattafesta et. al.] is a pressure spectra demonstrating the suppression of resonant cavity acoustics in a Mach .74 cavity flow. The device used in this case is similar to the earlier "piezo-wedge" – in this case it is a cantilevered metal flap (like a diving board), driven into first bending mode by a piezoceramic patch. The first thing to observe in this figure is that the forcing frequency is in the vicinity of the dominant Rossiter modes (just to the right of the first mode at about 550 hz), i.e. "low frequency", and that this forcing takes about 8 dB off the first mode. The second thing to notice is that it does this while having little or no effect on the broadband level. We will continue to see this same theme in subsequent experimental data – no evidence that low frequency forcing has any significant effect on broadband acoustic levels. Figure 16 [Ref. 21] shows that this same device achieved its highest levels of suppression (approximately 21 db) in a very low speed (roughly Mach .15) cavity flow.

Figure 17 [Ref. 22, Williams et. al.] shows acoustic suppression results for a Mach .48 cavity flow. In this case the zero mass addition, low frequency device is an acoustic driver, which forces a chamber connected to a slot near the leading edge of the cavity (a type of "synthetic jet"). The slot forces the cavity shear layer with a low speed inflow / outflow (zero net mass) in response to the movement of the driver. Similar remarks apply in this case. Forcing is in the "range" of Rossiter tones. This case is promising in that it shows the ability of a controller to simultaneously suppress multiple tones, but the level of suppression is not dramatic (less than 10 db). Figure 18 shows the best reported performance of this actuation technique, 18 dB at Mach .34. As before in the case of the low frequency piezo-flap, this "synthetic jet" zero mass addition device also leads to no appreciable change in the broadband sound pressure level, and also loses effectiveness as the Mach number increases.

Figure 19 [Ref. 23, Lamp and Chokani] shows best suppression results from another very low speed cavity experiment (Mach .15), using another version of a zero mass addition "synthetic jet". In this case the zero mass addition was managed using alternating positive outflow and powered suction (vacuum). Some "suppression" of the Rossiter cavity modes is evident, but with the presence of the strong forcing peaks, the net resulting suppression is only several dB. Two of the three forcing frequencies actually increased the peak level in the spectra. Consistent with the two other zero mass addition cases already discussed, no effect on the broadband level is present.

VI.2 Cavity Acoustic Control Using Steady Mass Addition

Figure 20 [Ref. 7] shows the effect of steady leading edge blowing on a Mach .8 cavity flow, as a function of mass flow rate. As can be discerned from the figure, increasing mass flow rates lead to both suppression of the tones, as well as a significant drop in the broadband level. Figure 21 [Ref. 24] shows the same type of suppression behavior from cavity leading edge blowing at Mach 1.5. The acoustic suppression in these cases is attributed mainly to displacement of the unstable free shear layer away from the cavity, leading to reduced impingement of vortical structures (and through feedback, subsequent reduced initial strength of those same vortical structures) on the rear wall of the cavity.

VI.3 Cavity Acoustic Control Using Positive Leading Edge Mass Addition With Low Frequency Pulsing

Pulsed blowing at the cavity leading edge has been popular as a candidate for cavity acoustic flow control, primarily because the more energy-frugal zero mass addition devices have proven to be largely unsuccessful in the range of realistic combat flight Mach numbers (Mach .8 to 1.5). Higher level perturbations from "positive mass addition" pulsed blowing devices, however, come at the expense of much higher mass flow rates.

Shaw and co-investigators [Refs. 1, 7, 25, 26, 27] have consistently pursued pulsed blowing as an acoustic suppression concept since 1995. Ref. 25 describes implementation of a low frequency pulsed blowing system in the leading edge of a weapons bay cavity within a 10% generic fighter model. Tests at Mach .85, and at various mass injection levels (.01 lbm/sec to 0.5 lbm/sec), show maximum suppression results of about 14 dB across all frequencies, occurring at a mass flow rate of .05 lbm/sec. (See Figs. 22 and 23). Later attempts to implement closed-loop control in the same model and wind tunnel (Fig. 24, Ref. 7) yielded no additional benefit. So-called "tonal" suppression in Ref 7 is quoted as high as 20 dB, but this measure of suppression is obviously very misleading, in that it ignores the rather large tone in the spectra created by the forcing itself (See Figure 24, and also the earlier explanation at the beginning of Section VI on undesirable mode growth in low frequency forcing).

Shaw, in collaboration with Lockheed Martin Corp., has also studied low frequency pulsed blowing in larger scale (20%) cavity models. Fig. 25 [Ref. 26] shows suppression due to pulsed blowing in a generic 20% scale cavity at Mach 0.85 . Three separate spectra with suppression (using different forcing frequencies) are plotted against a baseline (no suppression). There is no apparent effect of the pulsing on the spectra. Changing the frequency merely changes where the forcing peak appears, and has no effect on the dominant change in the broadband due to steady blowing. Fig 26 [Ref. 28] shows low frequency pulsed blowing suppression results on a 20% scale F-111 weapons bay cavity at Mach .9. The same result ensues. Varying the pulsing frequency resulted in no additional suppression over steady blowing. Even after redesigning the mass injection nozzles to provide enhanced pulse strengths (peak to peak amplitude) of roughly a FACTOR OF FOUR higher [see Ref. 27], this same technique yielded, at best, only 1-2 dB additional suppression over steady blowing.

It is now obvious, both from the results of section VI.1, and from the results of this section, that a significant portion (sometimes ALL) of the suppression from low frequency pulsed leading-edge blowing is due solely to the steady mass addition effect. This dominance of steady blowing over the pulse effect is seen at realistic Mach numbers (M > .8), where the naturally existing disturbance levels are quite high, and weak, low amplitude (low mass flow) pulsing would be fruitless. Pulsing the mass addition IS seen to be effective (approx. 20 dB suppression) for very low speed (M < .3) cavity flows, and marginally effective (approx. 10 dB suppression) up to M = .5.

VI.4 Low Frequency Acoustic Suppression Summary

In section VI.2, we showed that steady blowing at the cavity leading edge is a powerful suppression technique at relevant Mach numbers (up to **30 dB**), provided you can afford the relatively high mass flow rates (.3 lbm/sec at 1/10 scale – see Fig 20). We also saw in sections VI.1 and VI.3 that in the absence of steady blowing, one could achieve on the order of **10 dB** suppression with a low-frequency forcing technique, provided the Mach number was low enough (< .5). If steady mass blowing was present (and serves as the dominant suppression effect) additional pulsing yielded at best only several (1-2) dB additional suppression. A telltale sign of the steady mass addition being the "dominant effect" is a significant drop in the entire broadband level (up to 10 dB). So, the state of affairs for low frequency acoustic suppression at relevant (> M = .5) Mach numbers is that there are currently NO unpowered, and NO zero mass flow powered devices capable of providing suppression levels better than a passive spoiler (on the order of **10 dB**). Higher levels of suppression are possible with mass addition, but several different experiments point to the conclusion that pulsing the flow is unnecessary. **So there are no low frequency pulsing techniques which have proven to be more effective than spoilers in the Mach range of interest (.8 < M < 1.5).**

Let us contrast this state of affairs with some of the high frequency suppression results quoted in section IV. The rod in crossflow (an **unpowered**, zero mass addition device) delivered **14 dB** suppression at Mach .85, and **21 dB** suppression at Mach 1.19. If one were willing to consider a **powered** high frequency device, the resonance tube delivered **26 dB** at Mach .85, and an impressive **29 dB** suppression at Mach 1.19 (See Figures 13 and 14). Unfortunately, the powered resonance tube produces, in a very loose sense, a high frequency pulsed jet, and so some portion of its suppression must also be attributed solely to mass addition.

In spite of the ambiguity as to the cause of the suppression with the HF resonance tube, it should be obvious to even the casual observer that the suppression levels of the high frequency rod-in-crossflow at **supersonic conditions** are impressive. The dominant questions remaining are:

1) Do the rod in crossflow and resonance tube share a common "high frequency" suppression mechanism?
2)What is the nature of this mechanism? How is it different from low frequency suppression?
3) What percentage of the suppression in the case of the resonance tube is due to mass flow alone?

VII. Preliminary Theories / High vs Low Frequency Forcing

Stanek et. al. in References 11 and 19 provide several clues to the novel mechanism behind HF suppression. Figure 27 shows a schlieren image of a horizontal subsonic rectangular jet impinging upon a vertical wall. This "impinging jet" problem serves as a convenient analogue to the resonant cavity problem. Alternating light and dark round "blobs" reveal the presence of large scale coherent structures (and acoustic resonance). Figure 28 shows the same flow situation after the application of high frequency forcing from a resonance tube actuator. This flow shows no sign of large scale structures, and no evidence of acoustic resonance. Figure 32 shows a similar impinging round jet experiment where the high frequency forcing is accomplished using a bank of piezo wedges (see Figure 5). A similar destruction of the large scale coherent structures ensues. As shown in these schlieren photos, one possible explanation for the drop in the acoustic levels is the absence of large-scale vortical structures after the application of HF forcing. Figure 29 caricatures this first obvious difference between low frequency suppression and high frequency suppression in cavities, where LF forcing is described as a "detuning" mechanism (with large-scale structures still resident as evidenced by the acoustic spectra), and HF forcing is described as a "large-vortex" destroying operation.

The interesting question, of course, is what is causing the disappearance of the large-scale vortical structures? Is their disappearance simply a sign of suppression and not a cause? If we go back to the early <u>non-resonant</u> experiment by Glezer et. al., we see that the HF forcing in that experiment was accompanied by a substantial increase in the viscous dissipation (by at least an order of magnitude), and a fairly dramatic change in the broadband slope in the so-called inertial subrange (See Fig. 6). The first evidence of this type of change in a <u>resonant</u> flow is offered by Stanek et. al. [Ref. 11] in Figure 30 (compare to Fig. 6). There it is seen that the slope of the broadband spectra changes, depending upon whether one is forcing at low frequencies or high frequencies, implying that the RATE of energy flowing from low frequencies to high frequencies increases under HF forcing.

This evidence frames the argument over the source of the mysterious HF effect. A fundamental question is as follows: Is the HF mechanism similar to the rather obvious LF mechanism, where you are simply introducing a very small structure and this mode is "out-competing" it's neighbors? Or is the HF forcing different, perhaps somehow just "charging up" the viscous dissipation by increasing the flow of energy into the inertial subrange, and therefore, damping the growth of ALL instability modes? Put plainly, is HF forcing <u>encouraging</u> the growth of <u>one HF mode</u> or <u>discouraging</u> the growth of <u>all LF modes</u>?

Stanek et. al. [Ref. 11] surmised that the mechanism might be related to the fact that the forcing is occurring in the CONSERVATIVE (energy conserving) portion of the shear layer turbulence spectrum known as the inertial subrange. If the shear layer is receptive to accepting energy input in the inertial subrange, and the forcing frequency is still within the inertial subrange AFTER modification from forcing, then the rate of energy transfer from large to small scales MUST increase (since the energy cascade is conservative – what comes in must go out). It is possible that through HF forcing, the entire nature of the energy cascade is being redefined. Instead of the <u>turbulence production range</u> dictating the rate of energy dissipation (and feeding the smaller scales at **it's** own determined rate), perhaps now the <u>inertial subrange</u> is actually dictating the rate of turbulent energy production. This implies that the inertial subrange scales are actually DEMANDING more energy than the NORMAL turbulence production mechanisms can handle, with the net result being that the normally dominant large-scale cavity modes are literally being "starved" for energy (to feed the increased DEMAND of the inertial subrange).

Figure 31 lends some credence to the argument that it is forcing within the inertial subrange which produces the HF effect. In this figure, the "signature" of three high frequency devices are displayed for the same operating condition. Two of the **successful** devices (which produce the change in broadband and pronounced acoustic suppression), the rod in crossflow, and the resonance tube (mdot = .411) produce broad peaks, separated by roughly 1500 hz. Another unsuccessful HF device (which does not produce the characteristic HF slope change in the broadband), the piezo wedge, is represented by a very narrow peak, of similar amplitude to the first two devices. The message implied in this figure is twofold. First, the two devices which "worked" excited a mechanism which was <u>not</u> sensitive to forcing frequency. As long as the forcing was within the inertial subrange, the successful devices seemed to excite the HF mechanism. This bolsters the "accelerated conservative energy cascade" argument above. The other point is that the energy cascade is not "receptive" to all types of HF forcing. A device which produces a thin narrow spectral peak, even though it is of the right approximate amplitude and frequency, will not necessarily excite the mechanism. There may be some sort of "receptivity" or "minimum power" requirement somehow related to the breath (in frequency) of the forcing peak. It also hints at the notion that it may be a certain form of vorticity production (and not simply acoustic forcing) which is required to invoke the "high frequency" effect.

There is, of course, some danger in speculating along these lines. Both "successful" HF devices, in Figure 31, produce obviously similar effects on the broadband, but this is not proof that this is the cause of the bulk of the suppression. Both successful HF devices

also have some sort of "zero frequency" effect, and until that effect is separated from the high frequency signal effect, we can ONLY speculate as to cause and effect.

In light of our earlier discussion on low frequency pulsed blowing, and the fact that most of the suppression (at relevant Mach numbers) was due to STEADY mass flow, we must take pains to point out that this could also be the case with the HF resonance tube. In addition, in spite of the fact that the rod in crossflow eliminates the mass flow issue, there is also the "zero" frequency blockage effect of the rod which might be responsible for some or all of the suppression. Further testing is planned to attempt to resolve or clarify both these issues. What we CAN say at this time is that the rod in crossflow has already proven itself to be superior to the spoiler, at both subsonic and supersonic conditions [See Ref. 11], for comparable weight, size, and power (i.e. zero) input. The rod will be a serious contender for any future cavity suppression designs (and possibly as a retrofit to current cavity suppression systems).

It is also dangerous at the present time to declare "the destruction of large coherent vortical structures" as the CAUSE of the suppression of resonance in HF acoustic suppression systems. The disappearance of large coherent structures is at best right now, a *symptom* of the suppression of resonance. In fact, ANY technique (low frequency, high frequency, zero frequency) which successfully suppresses resonance should result in weakening of the large, dominant, coherent structures, which would be reflected in the flow visualization. The fact that we cannot settle this question now is a compelling statement for the need of high quality flow visualization in ALL resonant flow suppression experiments. Almost all of the cavity suppression experiments at realistic conditions provide only static and dynamic pressure data on the cavity walls and surrounding structure.

So far, the ONLY quantifiable "signal" proving whether suppression in a given situation is *possibly* due to HF forcing is the characteristic "shift" in the broadband (Figures 6 and 30). We have already seen that the existence of a clearly defined forcing peak (in the case of the piezo-wedge) at high frequency is not sufficient to cause this broadband slope "shift" which is the hallmark of the HF "effect". It may also be possible that one could produce this change in the broadband slope (indicative of an increase of energy in the high frequencies) without producing a characteristic forcing peak.

The essence of the argument for what might be high frequency acoustic suppression is captured in the original Wiltse and Glezer figure (Fig. 6). High frequency acoustic suppression does not necessarily require a peak at high frequencies which competes with other peaks. High frequency acoustic suppression derives its effect by raising the BROADBAND (not simply a single peak) over a RANGE of high frequencies. Forcing at a SINGLE high frequency raises the BROADBAND of the surrounding high frequencies. The key to this unique suppression is that the single frequency high frequency forcing somehow stimulates a mechanism where the BROADBAND high frequency range extracts energy from the BROADBAND low frequency range. The "change in slope" of the high frequency range broadband (Fig. 6) is direct evidence of the enrichment of the high frequencies at the expense of the low.

This characteristic shift in the broadband frequency could be used in the future as an acid test for the other supposition, that HF forcing can only be "engaged" within the inertial subrange. If this theory is true, then by lowering the forcing frequency, one should eventually hit the "crossover point", where you switch from HF to LF "physics". This should then be accompanied by the characteristic "jump" from one broadband slope to another (as seen in Figure 30). If all the speculations are on the mark, this crossover point will be at the point where the inertial subrange begins. This theory can only be tested experimentally by devising an actuator which does not change its physical characteristics (like size) as the operating frequency changes, and which can operate in a frequency band surrounding the expected crossover frequency.

The "high frequency effect" appears to be driven or triggered by raising the level of energy over an entire range of high frequencies (raising the broadband in the inertial subrange lowers the broadband in the turbulence production regime). This is why this type of suppression is independent of the forcing frequency, and what allows for a host of simplifications, such as optimization of actuators (for max amplitude) at a single frequency, forcing at a single frequency over a wide range of flight conditions, actuator simplicity (no moving parts), and no need for formal control systems (with or without feedback).

VIII. Summary – Major Differences Between LF Cavity Suppression and HF Cavity Suppression

We now summarize the perceived differences between LF and HF forcing in resonant cavity flows:

In Low Frequency forcing:

1) The energy addition takes place at frequencies near the dominate tones in a resonant cavity (turbulence production portion of the spectra).
2) The energy addition occurs in a non-conservative region of the frequency spectra where turbulence exchanges energy with the mean flow (turbulence production portion of spectra). The forcing mode ITSELF grows, and generates turbulence (large coherent vortical structures).
3) Strong resonant tones remain in the low frequency portion of the spectra after suppression (no simultaneous reduction of the Rossiter tones).

4) The candidate frequency (mode) supplied by the forcing is itself a significant source of unwanted noise, due to the fact that the largest structures (lowest frequencies) in the turbulent shear flow already contain the highest levels of energy in the spectra – and you are adding to that already high existing broadband SPL.
5) The resonant cavity is "detuned" (the feedback is out of phase with the forcing), but large coherent structures remain and serve as significant acoustic sources as they impinge upon the rear cavity wall.
6) The forcing frequency must adjust with changing Mach number, and must avoid coming too near the resonant Rossiter tones (to avoid reinforcing resonance). This requires the use of a control system. This also complicates the job of the actuator designer, who must sacrifice high amplitude at a single frequency for adequate performance over a prescribed bandwidth.

In High Frequency forcing:

1) The energy addition takes place at frequencies significantly higher (sometimes an order of magnitude or more higher) than the dominant tones in a resonant cavity (in the inertial subrange).
2) The energy addition occurs in a conservative region of the frequency spectra where turbulence does not exchange energy with the mean flow, and most energy flows from lower to higher frequencies (the inertial subrange).
3) All tones are suppressed in the low frequency portion of the spectra **simultaneously**, and no strong tones remain.
4) The energy supplied by the HF forcing does not become a problem itself, because the energy is added to that part of the spectra which has the least amount naturally – you are adding energy to a portion of the spectra with a naturally LOW broadband SPL.
5) All large coherent structures are minimized. This offers the lowest possible acoustic levels, because you have BOTH "detuned" the cavity flow, AND eliminated all significant acoustic sources due to impingement on the cavity rear wall – YOU HAVE ELIMINATED THE SOURCE FOR TONES.
6) The forcing frequency can remain constant (as long as changing conditions keeps the forcing within the inertial subrange). This eliminates the need for any control system. This also allows designers to make zero moving parts actuators with emphasis on maximum forcing level.

The terse defining statement of the philosophical difference between high and low frequency forcing is that high frequency forcing attempts to achieve suppression by directly manipulating the broadband at high frequency, causing a drain on the low frequencies, whereas low frequency forcing seeks to input a single dominant low frequency which will "out compete" the more dangerous natural (Rossiter) low frequency modes. Superimposed upon these basic mechanisms, in most cases, are zero frequency effects (like steady mass addition) which add to overall suppression levels, and complicate data interpretation. Zero frequency suppression causes a drop in the entire broadband level, **without** causing a change in the SLOPE of the HF range broadband, as seen in high frequency broadband manipulation.

Research is currently in progress to attempt to codify or eliminate from consideration individual perceived differences between HF and LF forcing from our list of possible suspects.

IX. Enter the Microjet / High Frequency Suppression of Impinging Jet Resonance?

During the same time frame as the cavity experiments at DERA, NASA was sponsoring research at Boeing focusing on acoustic suppression in impinging jet flows [Ref. 30]. Small-scale experiments using round jets forced by piezo wedges demonstrated suppression behavior similar to that seen in the Boeing rectangular nozzle work described earlier. Figure 32 shows "before" and "after" shots clearly demonstrating that the reduction in acoustic levels produced by HF forcing was accompanied by destruction of the large scale vortical structures in the flow.

Following the NASA work, AFRL (AFOSR – Air Force Office of Scientific Research) supported a very unique concept for the suppression of impinging jet resonance. Krothapalli et.al. [Ref 31] at Florida State University (FSU) produced dramatic acoustic suppression results in these impinging jet flows with a technique called the microjet.

To combat the resonance, Krothapalli et. al. installed a series of extremely small converging-diverging nozzles in the lip of the nozzle exit of a round jet. Figure 33 displays proof of the supersonic exit conditions for these nozzles (with diameters of .4 mm, relative to a main nozzle diameter of 28 mm.). When operated, the micronozzles consumed less than ½ percent of the core massflow of the main nozzle. The results were astounding. Figure 34 shows the spectra of the impinging round jet before and after activation of the microjets. The peak overall level drops by almost 50 dB! In addition, the broadband drops consistently by 10 dB across all frequencies.

The suspicion early on was that this suppression might be related to the suppression seen in the HF forcing cavity experiments. Due to the very small scale of the energetic small jets, and the fact that the presence of shock cells allowed for the presence of very small scale jet screech, it was postulated by several researchers that the mechanisms were the same.

One of the drawbacks to the microjet impinging jet experiments was, however, that there was no obvious forcing frequency present in the spectra [Fig. 34]. This might lead one to suspect that HF forcing is NOT responsible for the impinging jet acoustic suppression. To test this hypothesis, microjet leading edge inserts for the DERA cavity model were fabricated by the University of Florida under contract to Boeing, and Air Force Research Laboratory, and tested in February 2001. Preliminary analysis of the data

leads to the conclusion that steady blowing (not a HF effect) is most likely the dominant, if not the only cause of suppression in the case of microjets applied to cavity acoustic suppression, but further analysis is still underway.

Several other devices (in addition to the microjet) were tested in the Feb. 2001 DERA / AFRL test entry. These include two different "low mass flow" powered resonance tubes, a modified version of the original resonance tube bank (Figure 12) designed to kill the "resonance tube forcing" resonance and pass the same mass flow, and several rod / spoiler combinations. The data from that test is currently being analyzed and will be published in the near future.

X. Preliminary Numerical Simulations of High Frequency Forcing Behavior in Shear Layers

The first attempt to directly simulate the effect of high frequency forcing (high in the sense described in this review) in a shear layer was described in Cain and Rogers [Ref. 32, 2000. See also Ref 12, Cain et. al., 2001]. In this work, the pseudospectral free shear layer code used by Rogers and Moser [Ref. 33] and Moser, Rogers, and Ewing [Ref. 34] was applied to a plane wake under the influence of HF forcing. The intention was to attempt to simulate a situation similar to that seen in the Wiltse and Glezer experiments [Ref. 9]. In lieu of a more formal grid resolution study, Cain and Rogers use past simulations using this code as guidance for choice of mesh density. Fig. 35 shows a turbulent velocity spectra after HF forcing (simulated), and comparison with Figure 6 (experimental) demonstrates that the simulation resolution is adequate.

Cain and Rogers [Ref. 32] examines the effect of HF forcing on both fully turbulent and transitional wake flows. They find that HF excitation of a fully turbulent plane wake shows only a weak transient effect. In contrast, HF excitation applied to a transitional plane wake has a significant lasting impact. Figure 36 shows a plot of integrated turbulent kinetic energy vs time for the transitional simulation, with and without forcing. The simulation shows a reduction in this quantity by 20 % at the time the simulation was stopped (with more reduction possible). Figure 37 shows that integrated turbulence dissipation rate is increased by 14 %. This figure also shows that if the HF perturbation is applied "late" in the life of the transition process, that it has no lasting effect. In addition to the dissipation being enhanced, Figure 38 shows the integrated rate of turbulent kinetic energy production is also diminished by 24%. Cain et. al. [Ref. 12] speculate that these effects may be due to nonlinear interactions between high amplitude high frequencies and the production scales, with the net effect being a reduction of the correlation coefficient between components of the Reynolds stress tensor. Further analysis is required to substantiate this claim.

While not directly applicable to the case of high-speed cavity flow, these results are intriguing. Certainly, the cavity flow shear layers are "transitional" in the same sense as Cain's plane wake flow is – evolving from boundary layer type turbulence to a "free shear layer" variety. Obviously, more high fidelity simulations (in high speed cavites) are required to enable a direct comparison to be made.

XI. Conclusions & Future Work

Over the relevant Mach range of interest for military high-speed cavities ($.8 < M < 1.5$), an "average" rule-of-thumb value for expected suppression using a passive spoiler is roughly 10dB. Steady leading edge blowing (relatively high mass flow rates) has been shown in numerous tests (including flight test) to be very effective in this Mach range of interest (max suppression on the order of 20 dB). Superimposing pulsing over high levels of steady blowing has no significant additional suppression effect (1-2 dB OASPL). A review of all low frequency pulsing techniques reveals that there is no experimental data demonstrating that pulsing is more effective than the standard leading edge spoiler in the relevant Mach range of interest.

Two high frequency devices (a rod in crossflow, and HF resonance tube) have demonstrated significant suppression improvements over spoilers (from 14 to 29 dB) in the .8 to 1.5 Mach range. The resonance tube device emits significant amounts of mass flow, and the percentage of suppression due to steady mass addition is currently under investigation.

Unique attributes of high frequency flow control (vs conventional, low frequency control) have been convincingly established in low speed flows (Ref. 9). Similar detailed measurements still need to be taken and interpreted for high-speed flows. Numerical studies have produced interesting insights into the nature of the high frequency flow control mechanism, but the expense of high fidelity simulations have limited the depth (extent) of these simulations. Conclusions at this time must be considered preliminary.

In spite of the obvious power of the emerging class of HF actuators, and their impact on resonant acoustic problems, several important matters of research remain. Attempts to scale these devices to flight conditions will likely depend upon a clearer understanding of the basic physics involved. Listed below are a limited selection of questions and issues remaining.

What constitutes sufficient "frequency or spectral breadth" of forcing signal for a HF device appears to be a function of experiment scale and Mach number. The piezo wedge devices (which eliminate the sticky question of the effect of mass flow) which are completely ineffective in the experiments described in this paper (and in Ref. 11), were shown to evoke the desired effect in a smaller scale, lower speed "bench" experiment described in Ref. 16.

Future studies will focus on answering some of the following questions:

What percentage of the suppression due to the powered resonance tube can be attributed solely to mass injection effects?

What is the range of effective HF forcing frequencies (the inertial subrange?)? Is there an optimum? Why?

Is it possible to force at too high a frequency?

How do these model-sized demonstrations scale-up to full scale?

Do other LF devices show changes to the broadband similar to the spoiler (and therefore dissimilar to the HF devices)?

Can we quantify the " frequency breadth" requirement evident in the experimental data?

Is the microjet mechanism the same as that produced by the rod and powered resonance tube devices? What percentage of the suppression for that device is due solely to mass flow?

XI. References

1. Shaw, L. , "Active Control For Cavity Acoustics", AIAA-98-2347.
2. McGrath, S. & Shaw, L. 1996 Active Control of Shallow Cavity Acoustic Resonance, AIAA-96-1949.
3. Williams, D. R., Fabris, D., Iwanski, K., and Morrow, J., "Closed-Loop Control In Cavities With Unsteady Bleed Forcing", AIAA-2000-0470.
4. Raman, G., Raghu, S., and Bencic, T., "Cavity Resonance Suppression Using Miniature Fluidic Oscillators", AIAA-99-1900.
5. Cattafesta, L. N. III, Shukla, D., Garg, S. & Ross, J. A. 1999 Development of an adaptive weapons-bay suppression system. AIAA-99-1901.
6. Mongeau, L., Kook, H., Franchek, M. A., "Active Control Of Flow-Induced Cavity Resonance", AIAA/CEAS AeroAcoustics Meeting, Toulouse, France, June 1998.
7. Shaw, L. and Northcraft, S., "Closed-Loop Active Control For Cavity Acoustics", AIAA-99-1902.
8. Maines, B. H., Robarge, J. E., Welterlen, T. J., and Smith, B. R., "Weapons Bay Acoustic Suppression From A Rod in Crossflow", Active Robust ConTrol of Internal Cavities (ARCTIC) Workshop Presentation, AIAA Aerospace Sciences Meeting, January, 2001.
9. Wiltse, J.M., and Glezer, A., "Direct Excitation of Small-Scale Motions in Free Shear Flows, Phys. Fluids, Vol. 10, No. 8, pp2026-2036, 1998.
10. Yeung, P.K., Brasseur, J. G., and Wang, Q., "Dynamics of Direct Large-Scale Couplings in Coherently Forced Turbulence: Concurrent Physical-Space and Fourier-Space Views", J. Fluid Mech., 1995, Vol. 283, pp 43-95.
11. Stanek, M. J., Raman, G., Kibens, V., Ross, J. A., Odedra, J., and Peto, J. W., "Control of Cavity Resonance Through Very High Frequency Forcing", AIAA/CEAS Aeroacoustics Meeting, Lahaina, Hawaii, AIAA 2000-1905.
12. Cain, A. B., Rogers, M. M., Kibens, V., and Raman, G., "Simulations of High-Frequency Excitation of a Plane Wake", AIAA-2001-0514.
13. Ho, C. M. and Huerre, P., "Perturbed Free Shear Layers", Annual Review of Fluid Mechanics, Vol. 16, p. 365, 1984.
14. Cain, Alan. Private Communication, 1997.
15. Raman, G., Kibens, V., Cain, A., and Lepicovsky, J., "Advanced Actuator Concepts For Aeroacoustic Control", AIAA-2000-1930.
16. Brocher, E., Maresca, C., and Bournay, M. H., "Fluid Dynamics of the Resonance Tube", J. Fluid Mech. (1970), Vol. 43, Part 2, pp 369-384.
17. Thompson, M.C., Hourigan, K., Welsh, M.C., and Brocher, E., "Acoustic Sources in a Tripped Flōw Past a Resonator Tube", AIAA Journal, Vol. 30, No. 6, June, 1992.
18. Brocher, E., and Duport, E., "Resonance Tubes in a Subsonic Flowfield", AIAA Journal, Vol. 26., No. 5, 1987.
19. Stanek, M.J., Raman, G., Kibens, V., Ross, J. A., Odedra, J., and Peto, J.W., "Suppression of Cavity Resonance Using High Frequency Forcing – The Characteristic Signature of Effective Devices", 7th AIAA/CEAS Aeroacoustics Conference, 28-30 May, 2001.
20. Cattafesta, L. N. III, Shukla, D., Garg, S., and Ross, J. A., "Development of an Adaptive Weapons-Bay Suppression System", AIAA-99-1901.
21. Cattafesta, L. N., Garg, S., and Washburn, A. E., "Piezoelectric Actuators For Fluid-Flow Control", Proceedings of the S.P.I.E., 3044:147-157, 1997a.
22. Williams, D. R., Fabris, D., Iwanski, K., and Morrow, J., "Closed-Loop Control In Cavities With Unsteady Bleed Forcing", AIAA 2000-0470.
23. Lamp, A. M., and Chokani, N., "Control Of Cavity Resonance Using Steady and Oscillatory Blowing", AIAA 99-0999.
24. Grove, J. E., Birkbeck, R. M., and Kreher, J. M., "Acoustic and Separation Characteristics with Bay Leading Edge Blowing", AIAA 2000-1904.
25. Shaw, L., "Wind Tunnel Test Results For Active Suppression of Weapons Bay Acoustics", WL-TM-97-3109, Nov. 1997.
26. Shaw, L., "High Speed Application of Active Flow Control For Cavity Acoustics", AIAA-2000-1926.

27. Shaw, L., Smith, B., and Welterlen, T., "Actuator Optimization For Active Flow Control Of Cavity Acousics", AIAA-2001-2217.
28. Welterlen, T. J., "Active Weapons Bay Noise Suppression", FZM-8723, Final Report, Prepared by Lockheed Martin Aeronautics, for U. S. Air Force under Contract No. F33615-99-C-3218.
29. Raman, G., and Kibens, V., "Active Flow Control Using Integrated Powered Resonance Tube Actuators", AIAA-2001-3024.
30. Kibens, V., Wat, J.K., and Alvi, F.S., "High Frequency Excitation For Jet Noise Reduction", NASA Report CRAD-9310-TR-6155, October 1999.
31. Krothapalli, A, Elavarasan, R., Alvi, F., and Shih, C., "Active Control of Supersonic Impinging Jets", NATO RTO Symposium On Active Control Technology, Braunschweig, Germany, 8-10 May, 2000.
32. Cain, A. B. and Rogers, M. M., "High Frequency Excitation of a Plane Wake", Stanford Center For Turbulence Research, Annual Research Briefs, 2000.
33. Rogers, M. M., and Moser, R. D., "Direct Simulation of a Self-Similar Turbulent Mixing Layer", Physics. Of Fluids, Vol. 6, pp 903-923, 1994.
34. Moser, R.D., Rogers, M. M., and Ewing, D. W., "Self-Similarity of Time-Evolving Plane Wakes", Vol. 367, pp 255-289, 1998.

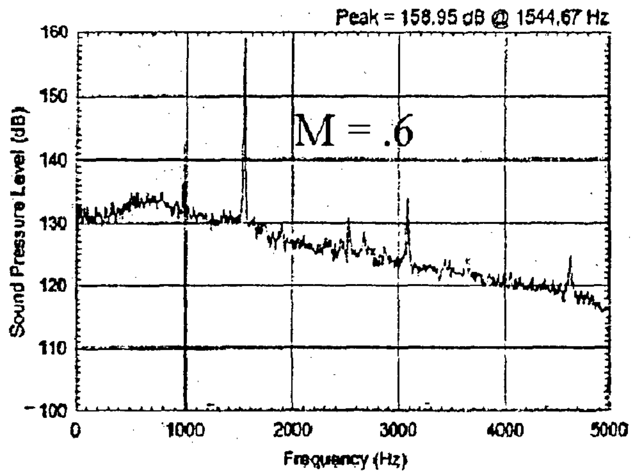

Figure 1. 1/10[th] Scale Cavity Spectra at Mach .6 – Before High Frequency Suppression (Ref. 2)

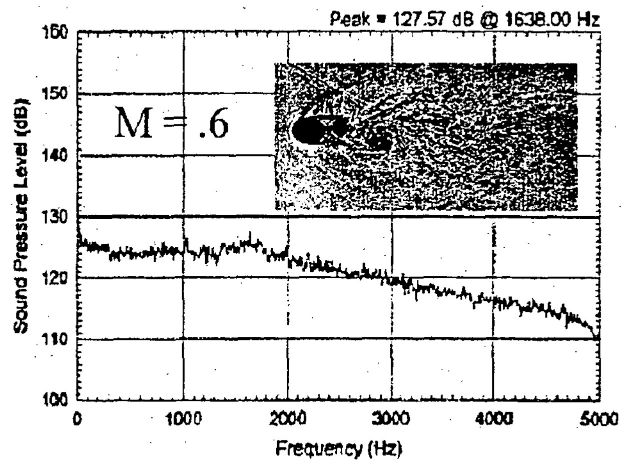

Figure 2. 1/10[th] Scale Cavity Spectra at Mach .6 – After High Frequency Suppression (Ref. 2)

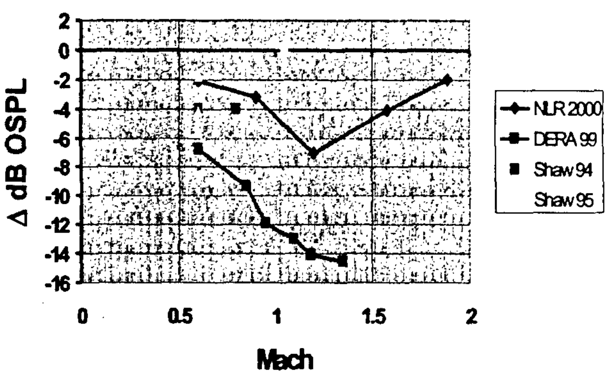

Figure 3. Historical "Rod in Crossflow" Acoustic Suppression Data (Ref. 8). Numbers in legend correspond to year of experiment.

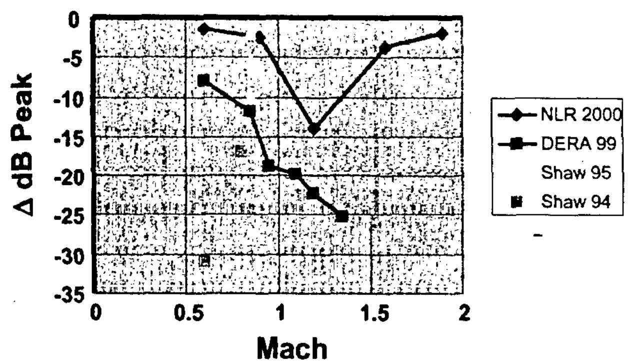

Figure 4. Historical "Rod in Crossflow" Acoustic Suppression Data (Ref. 8). Numbers in legend correspond to year of experiment.

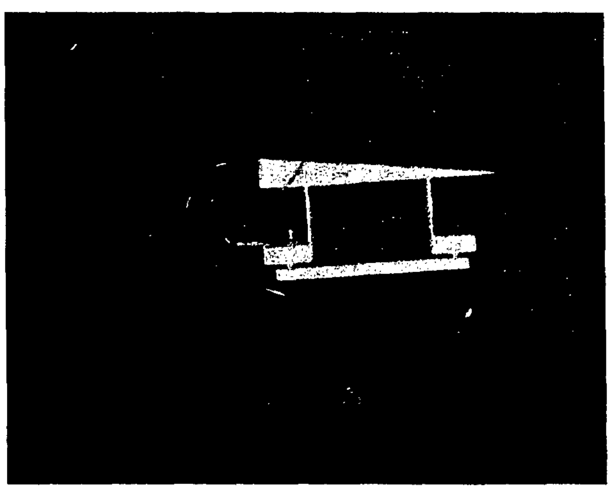

Figure 5. Close-up of a Single PiezoCeramic Driven Wedge (Ref. 11)

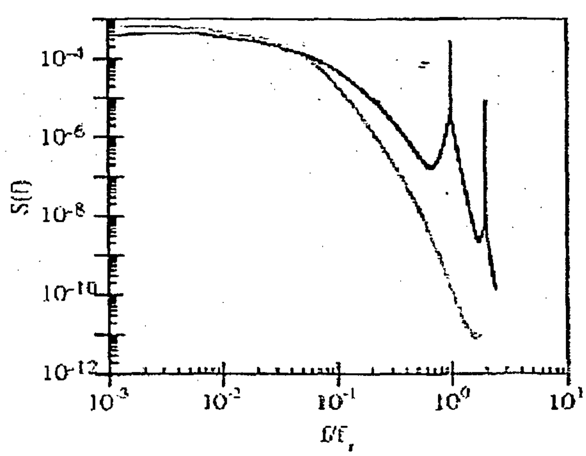

Figure 6. Effect of High Frequency Forcing On A Laboratory-Scale Free Shear Layer (Ref. 9)

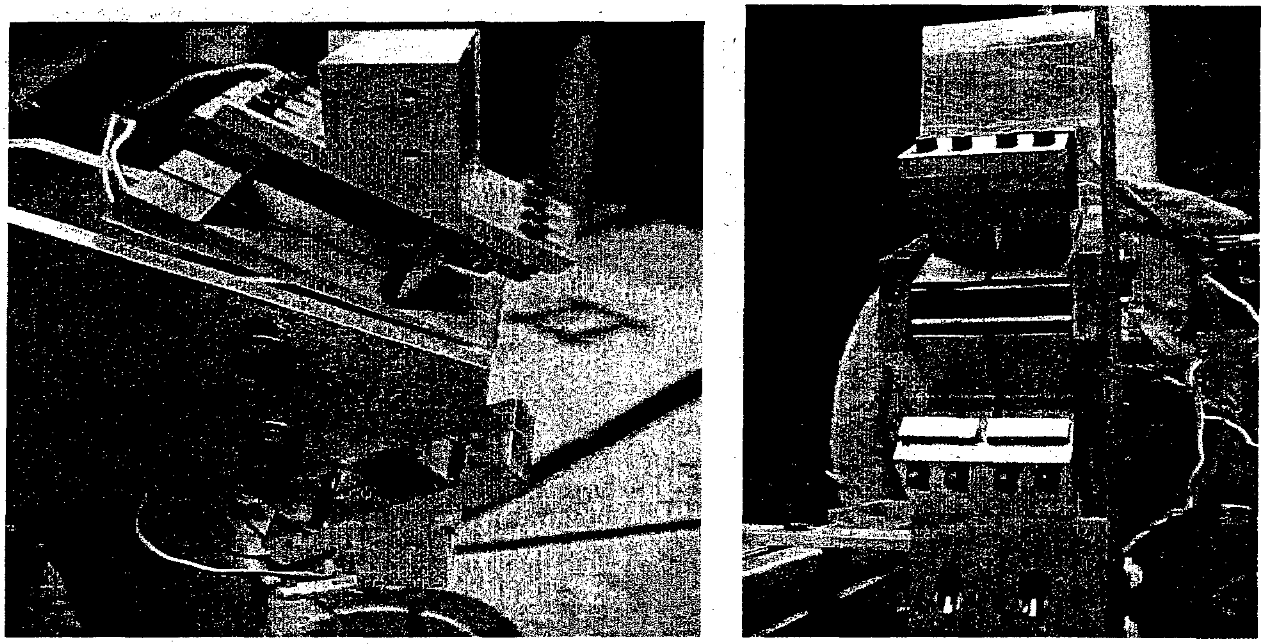

Figure 7. Side and Front View of Boeing "High" Frequency Excitation Jet Edge-Tone Reduction Experiment (Simulated Cavity) Ref. 15.

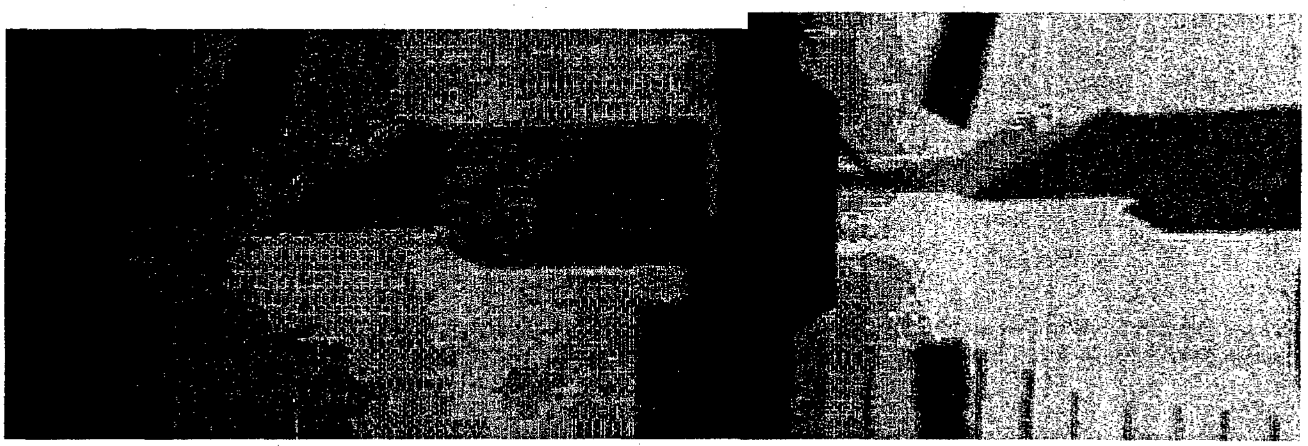

Figure 8. Side View Of Jet Edge Tone Experiment. Left inset Without HF Excitation. Right Inset With HF Excitation (Ref. 15).

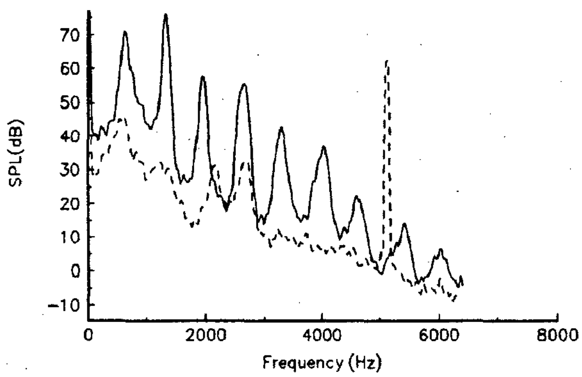

Figure 9. Acoustic Spectra in Jet Edgetone Experiment, Before and After HF Excitation. (Ref. 15)

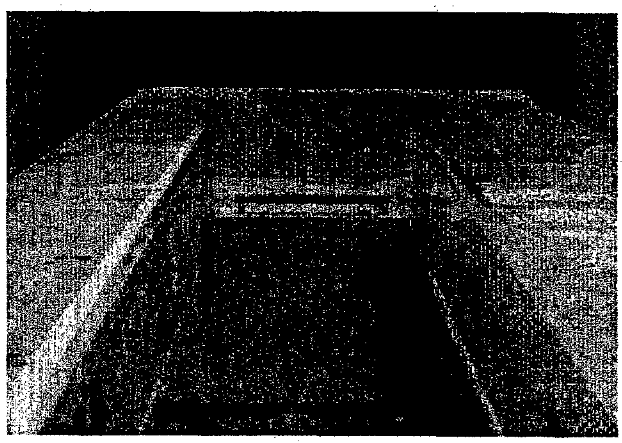

Figure 10. View (from rear of cavity) of Rod-in-Crossflow Device Installed in the DERA 1/10th scale cavity model. Vertical doors and surrounding flat plate visible in photo. (Ref. 11)

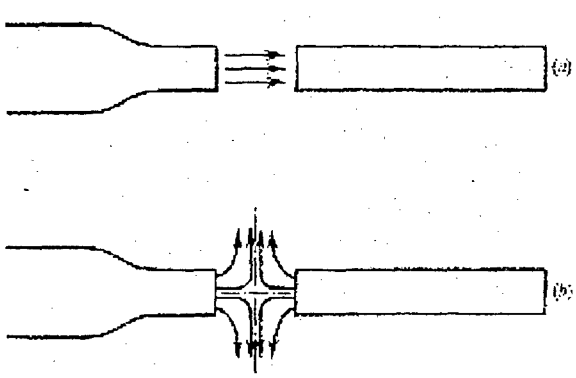

Figure 11. Schematic of Powered Resonance Tube Concept (Ref. 16)

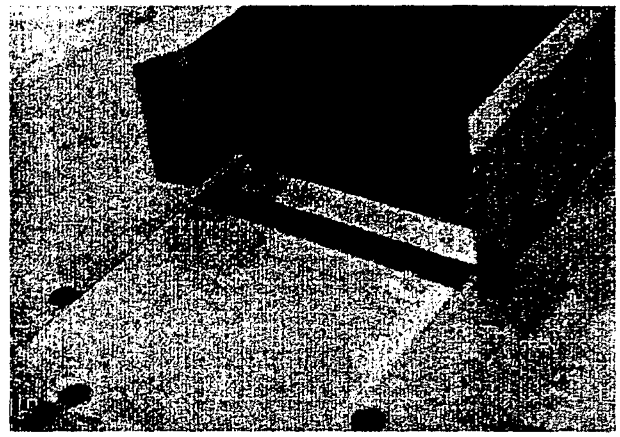

Figure 12. Close-up of Powered Resonance Tube Installation (Ref. 11).

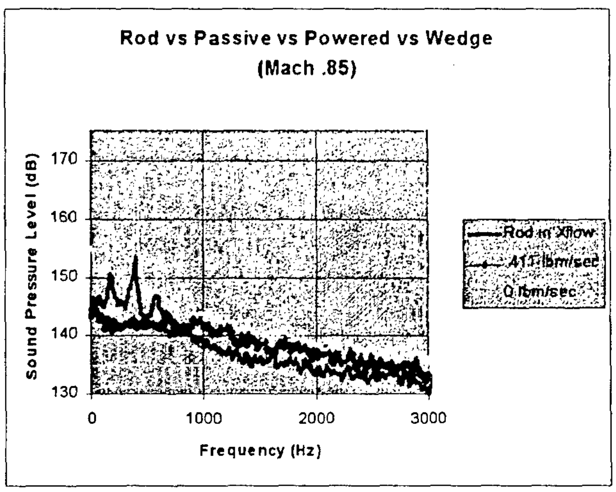

Figure 13. Suppression Effectiveness of Rod vs Powered Resonance Tube at Mach .85 (31 kHz sampling rate) Ref. 11.

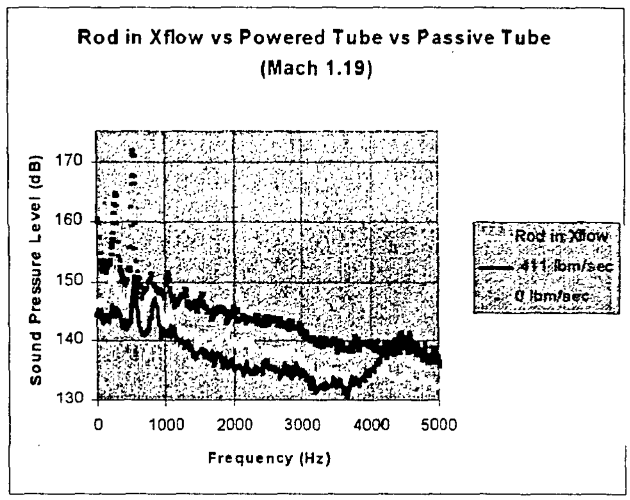

Figure 14. Suppression Effectiveness of Rod vs Powered Resonance Tube at Mach 1.19. (31 kHz sampling rate) Ref. 11.

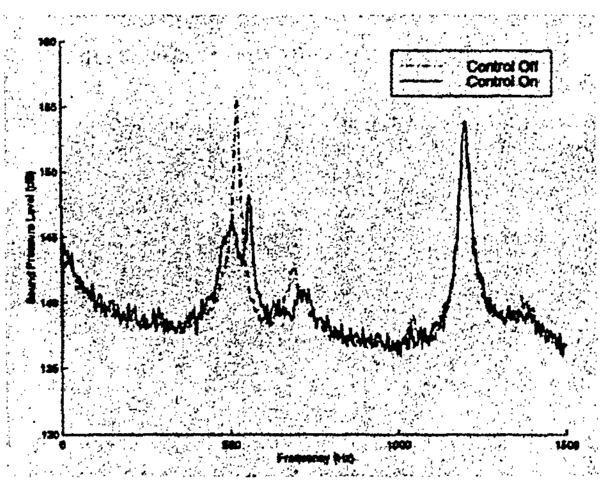

Figure 15. Reduction of 1st Mode SPL at Mach 0.74 in the PCT at NASA Langley Research Center (Ref. 20).

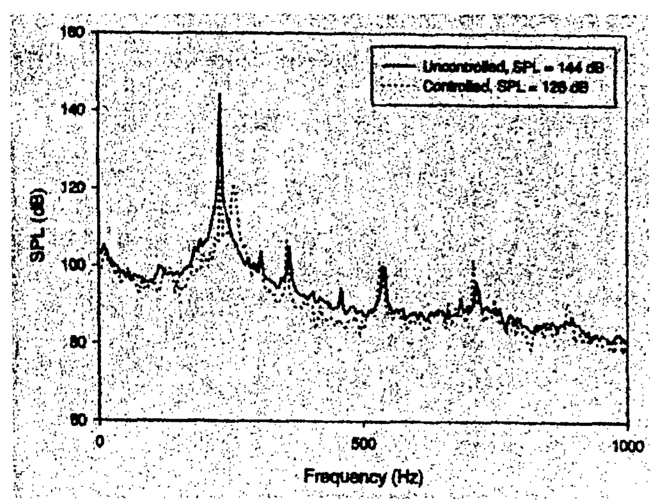

Figure 16. Measured Sound Pressure Level On Cavity Floor With and Without Piezo Flap Control (Ref. 21).

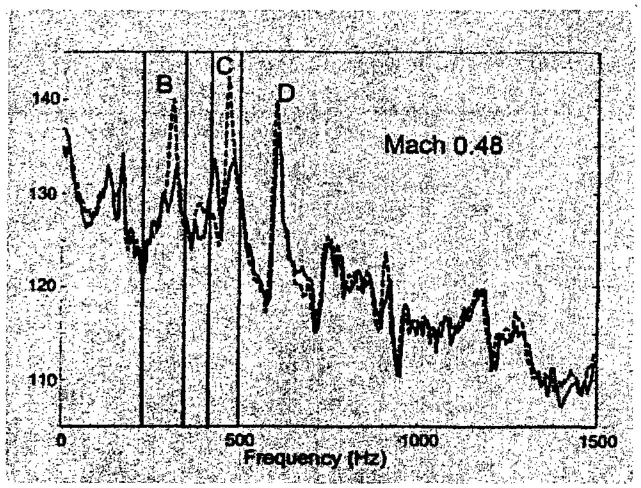

Figure 17. Acoustic Suppression Using Speaker-Driven Synthetic Jet. Multiple Pass Bands in feedback allow multimode suppression (Ref. 22)

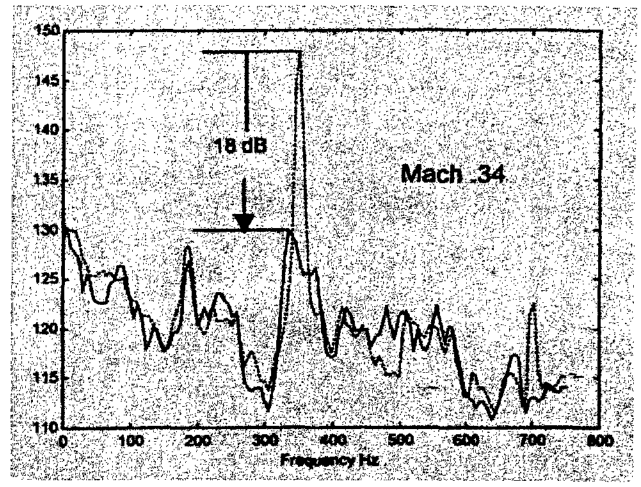

Figure 18. Acoustic Suppression Using Speaker-Driven Synthetic Jet. Closed-Loop Control, L/D = 5.0, M= .34 (Ref. 22)

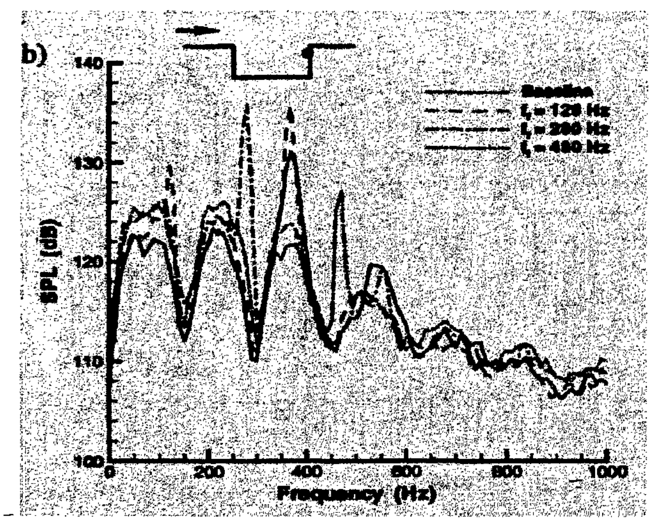

Figure 19. Spectra For Oscillatory Blowing (Zero Net Mass Addition). Rear Wall Location (Ref. 23).

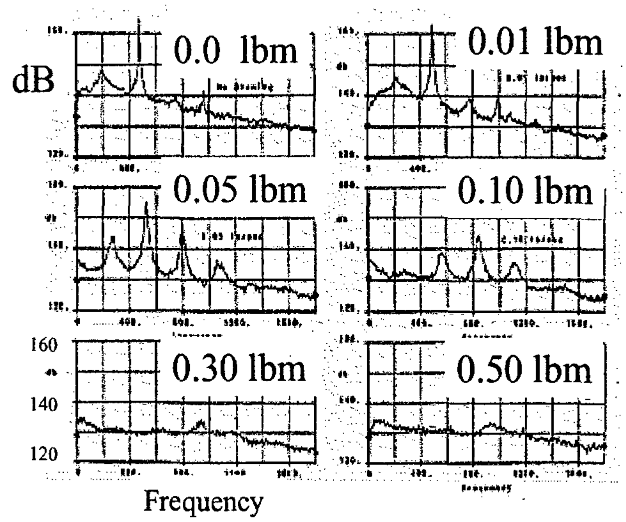

Figure 20. Suppression of Cavity Acoustic Levels With Steady Leading Edge Blowing at Mach .8 (1/10th scale – Ref. 7).

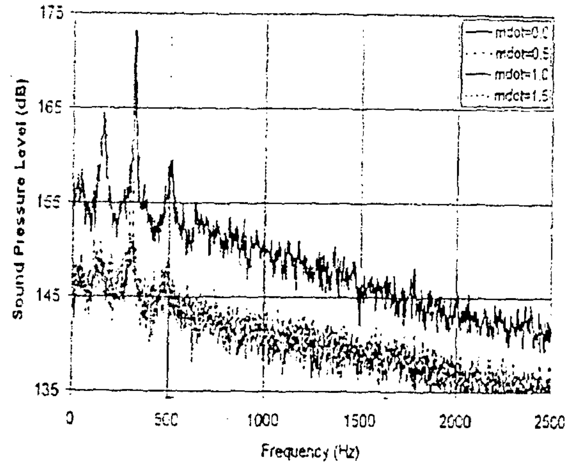

Figure 21. Cavity Acoustic Suppression Due To Steady Leading Edge Blowing. 1/5th Scale, Mach 1.5 (Ref. 24).

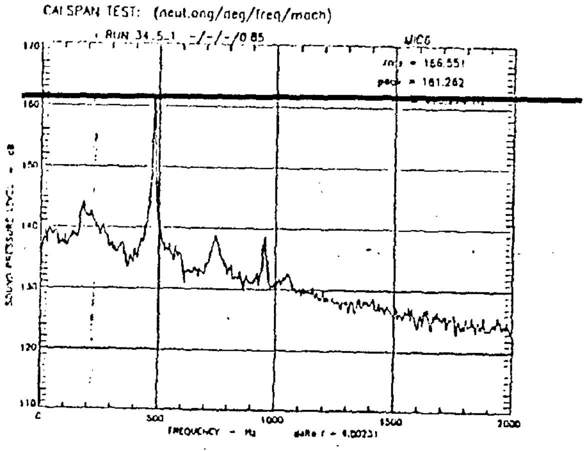

Figure 22. Baseline, Unsuppressed Spectra at Mach .85 (Ref. 25).

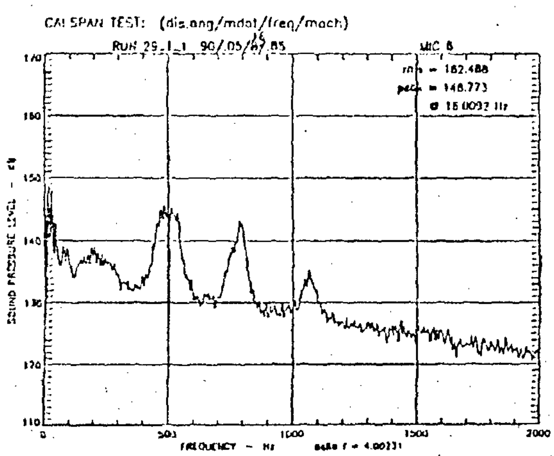

Figure 23. Suppressed Spectra. Pulsed Blowing @ 16 Hz, 0.05 lbm / sec (Ref. 25).

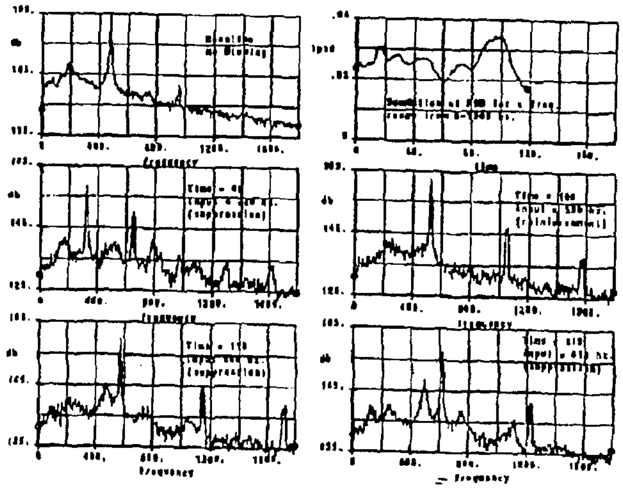

Figure 24. Suppression At Various Times Due To Pulsed Blowing. Continuous Sweep In Frequency(0 to 2000 Hz.), Mach 0.85 (Ref. 7).

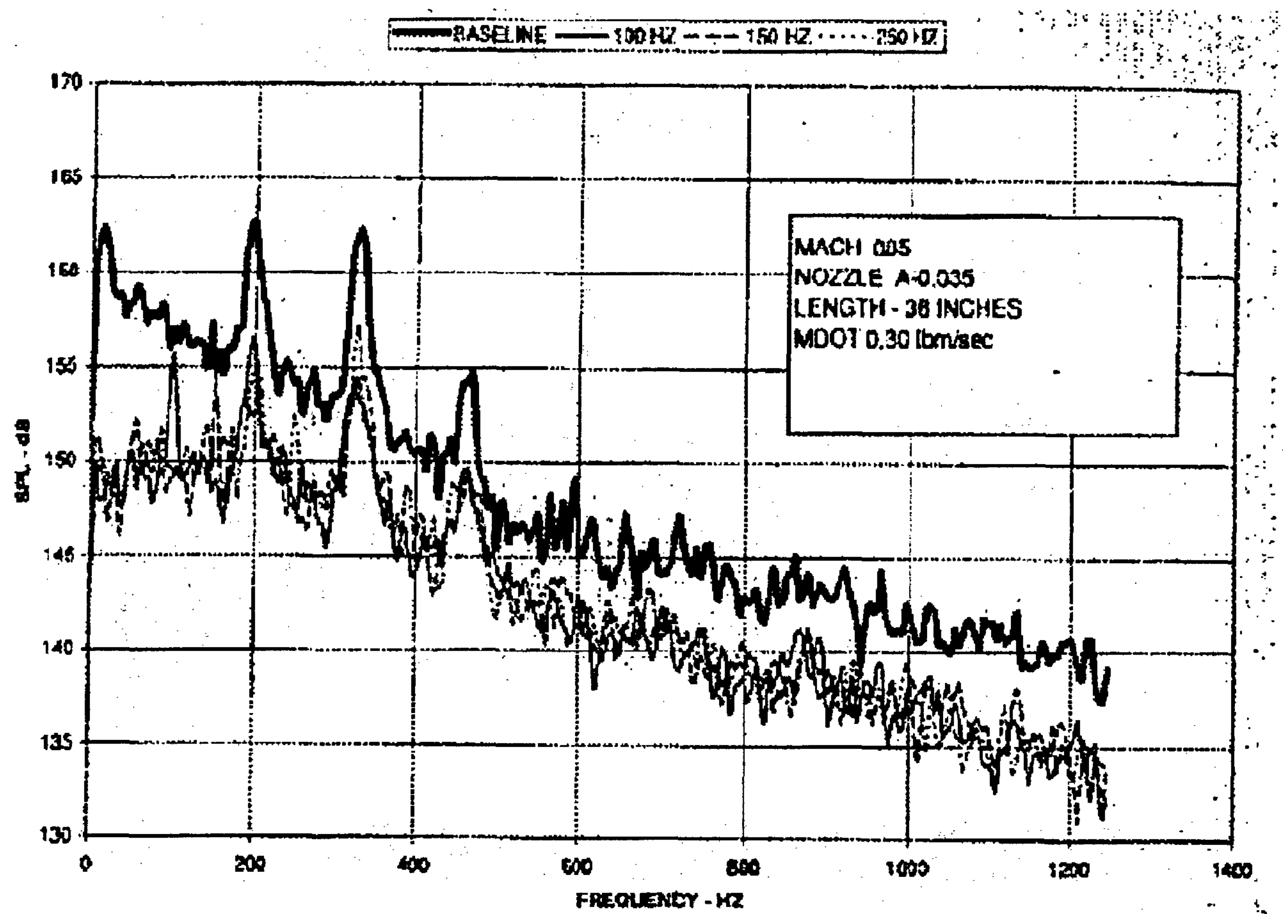

Figure 25. Figure Indicating That Change in Pulsing Frequency Has No Effect On Acoustic Suppression. Pulsed Blowing, 1/5th Scale, Mach .85, Forcing @ 100-250 hz (Ref. 26.).

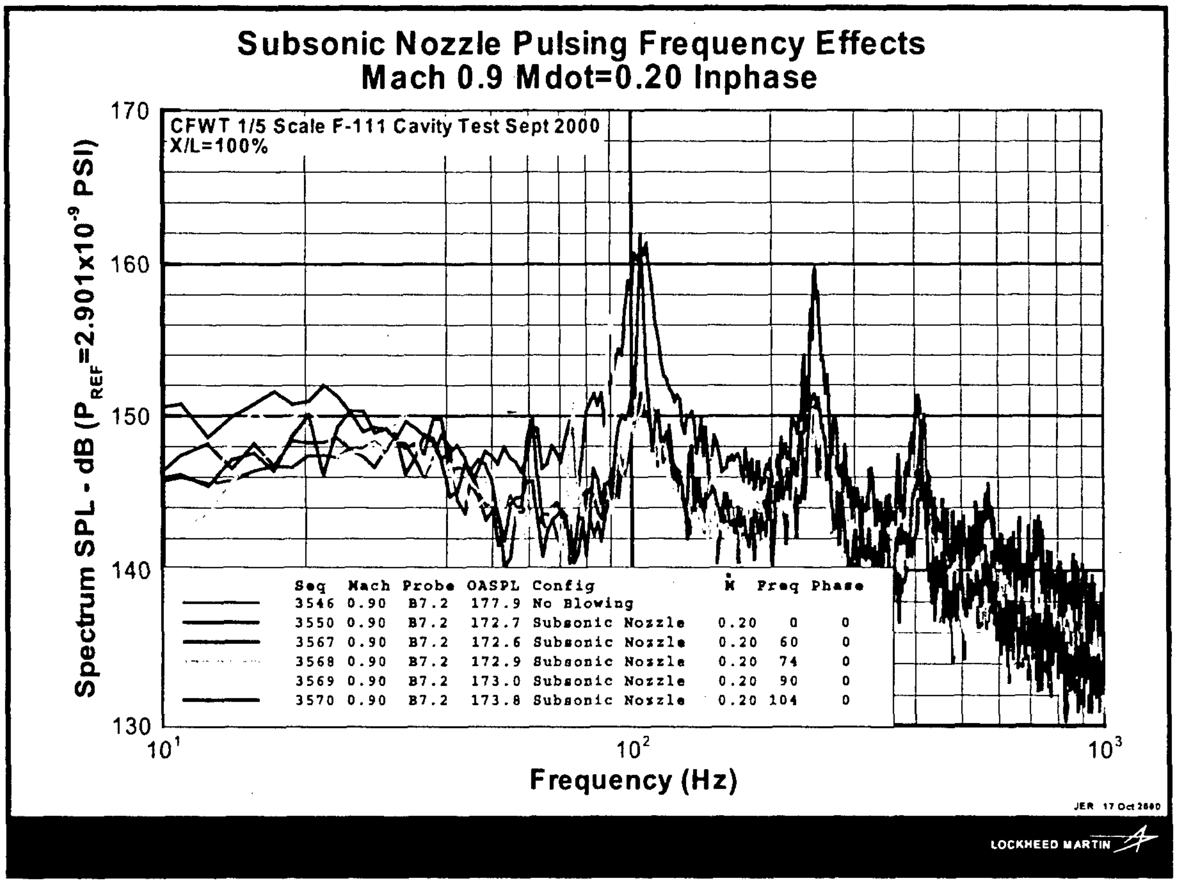

Figure 26. 20% Scale Test of Rotary Valve / Subsonic Nozzle Combination. No Additional Suppression Observed Over Steady Blowing (Ref. 28).

Figure 27. Integration of High Frequency Resonance Tube Near Lip Of Rectangular Jet Nozzle. Resonance Tube Turned Off (Ref. 29).

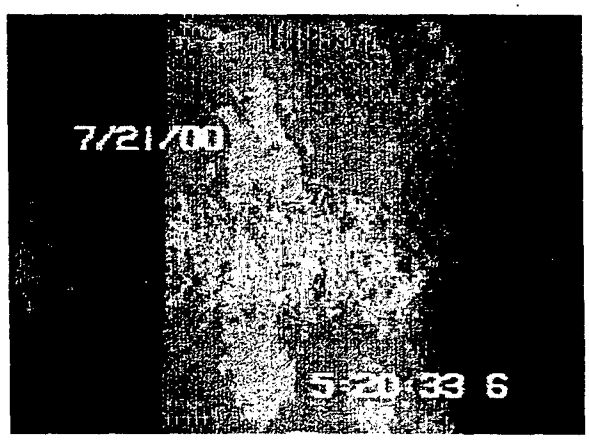

Figure 28. . Integration of High Frequency Resonance Tube Near Lip Of Rectangular Jet Nozzle. Resonance Tube Turned On (Ref. 29).

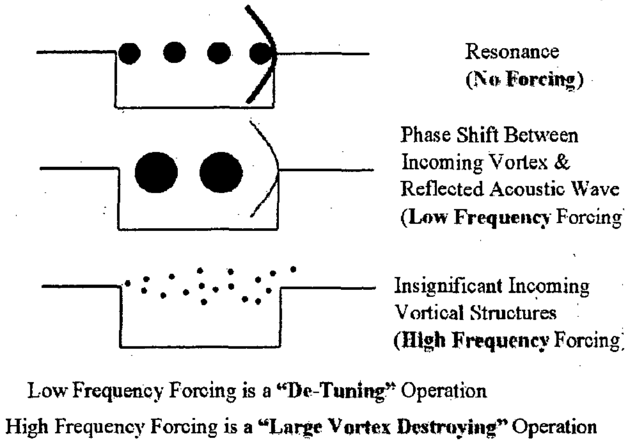

Figure 29. Schematic Illustrating Conceptual Differences Between No Forcing (Top), Low Frequency Forcing (Middle), and High Frequency Forcing (Bottom). (Ref. 11)

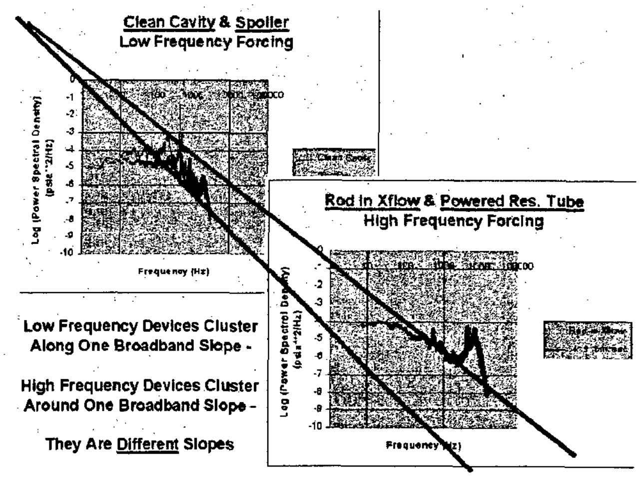

Figure 30. High Frequency Forcing Effect on Slope of Broadband Level (Ref. 11).

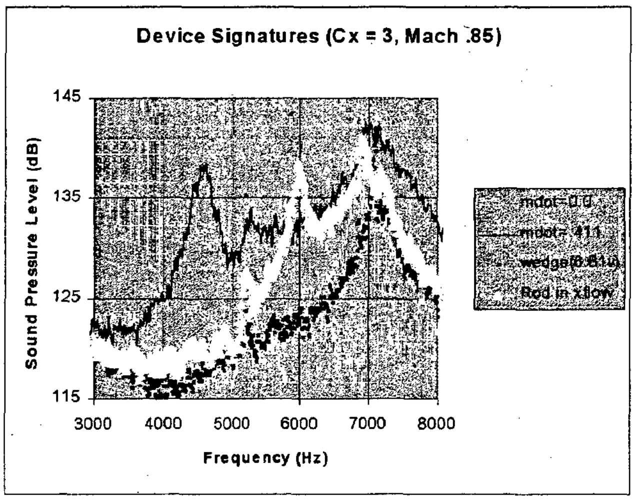

Figure 31. Spectral Signatures of Various Acoustic Suppression Devices. (Ref. 19)

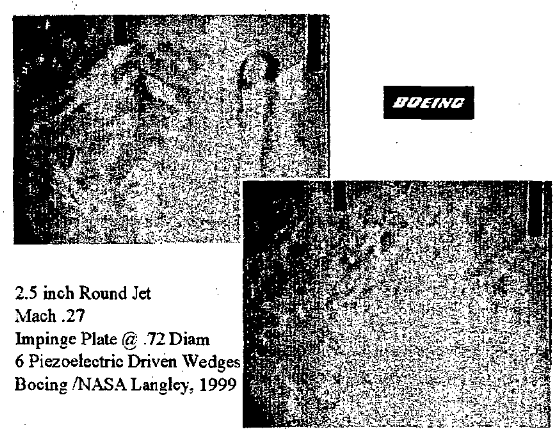

Figure 32. Schlieren Image of Jet Impinging on a Perpendicular Flat Plate. Top Image (With Large Coherent Structures) Before Suppression. Bottom Image (With No Visible Coherent Structures) After High Frequency Suppression (Ref. 30)

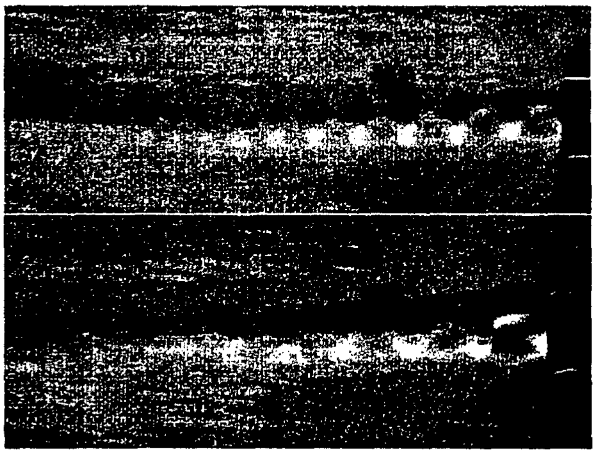

Figure 33. Schlieren Showing Periodic Shock Cells in 400 micron diameter Microjets, Top @ Po= 68 psi, Bottom @Po = 110 psi (Ref. 31)

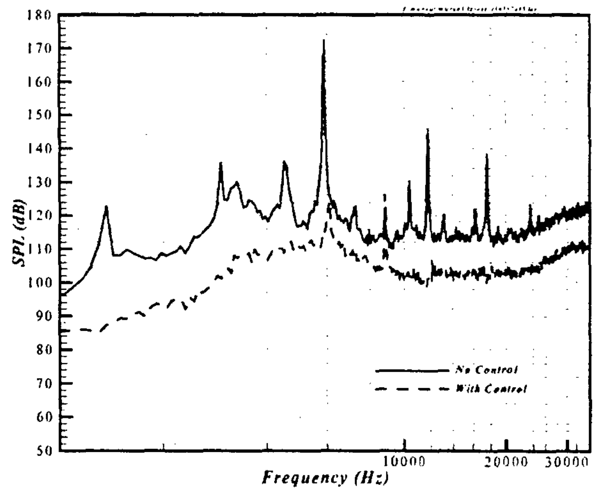

Figure 34. Spectra Showing Peak & Broadband Levels Significantly Reduced In Impinging Jet Problem With Application of Supersonic Microjets (Ref. 31).

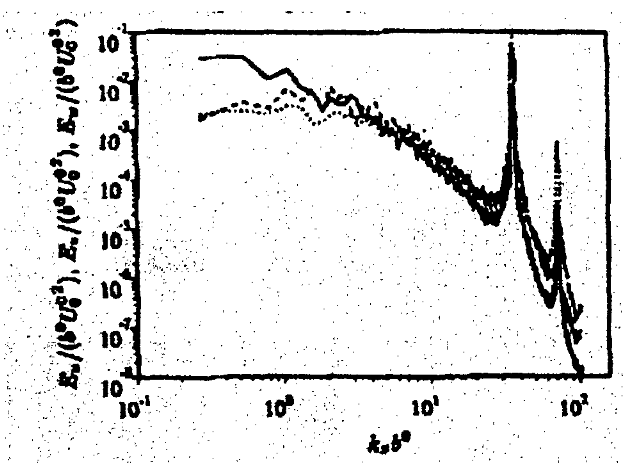

Figure 35. Spectra From Simulation of High Frequency Forcing Experiment (Ref. 32). Compare With Behavior Shown in Figure 6.

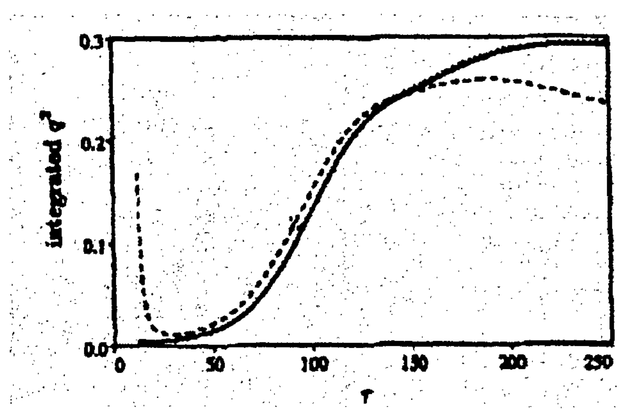

Figure 36. Integrated Turbulent Kinetic Energy As A Function Of Time (Ref. 32).

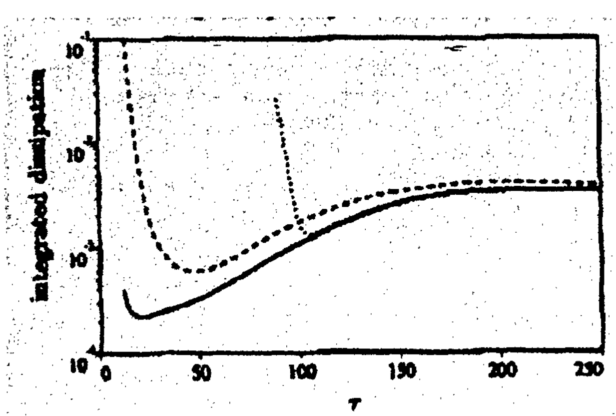

Figure 37. Integrated Dissipation Rate As A Function of Time (Ref. 32).

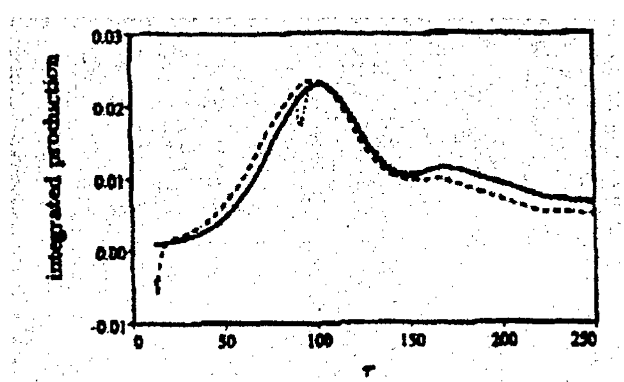

Figure 38. Integrated Rate Of Production Of Turbulent Kinetic Energy As Function of Time (Ref. 32).